Note: large # of AMO talks (colloq & seminars) this week

Lecture 5: hyperfine structure

Readings: Foot Chapter 6.1-6.2

So far: - gross structure from electrostatic interactions

- fine structure, in large part from the electron spin

Today: - hyperfine structure

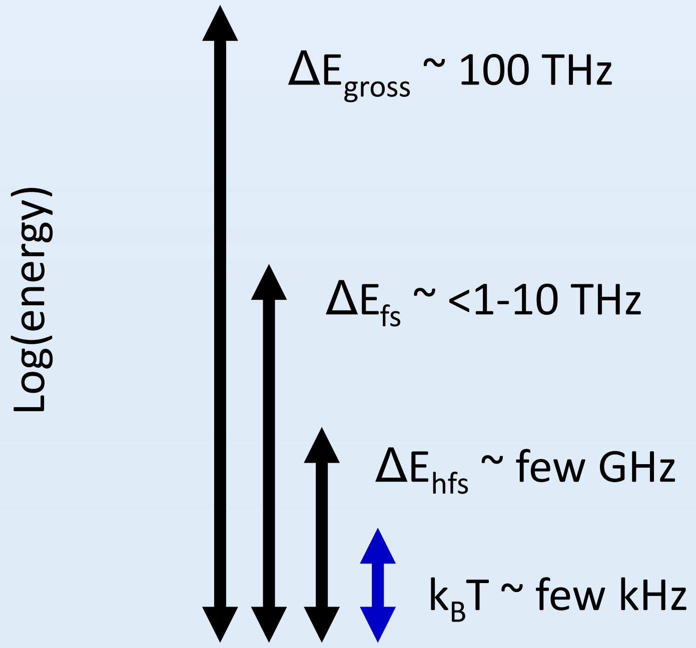
- we'll mostly be interested in new level structure coming from the coupling of the spin of the nucleus and the total angular momentum of the electron

- also, energy corrections due to various nuclear properties

The end of the road

$|F, m_F\rangle$ states are the ones utilized in low-energy (ultracold) atomic physics experiments

→ Thermal energy scales will be below ΔE, only coherent control of internal D.O.F.

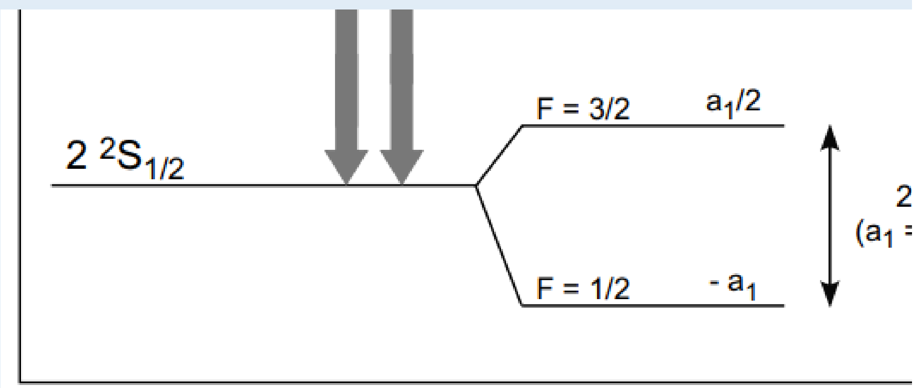


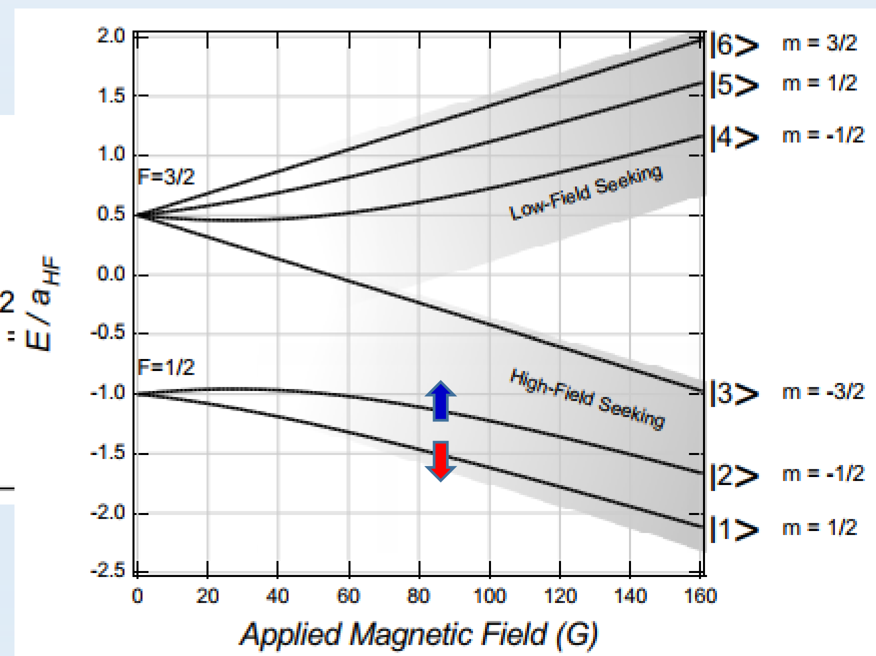
pseudo-spin states

$|F, m_F\rangle$ states are the ones utilized in low-energy (ultracold) atomic physics experiments

→ Thermal energy scales will be below ΔE, only coherent control of internal D.O.F.

Example – lithium 6 hyperfine states





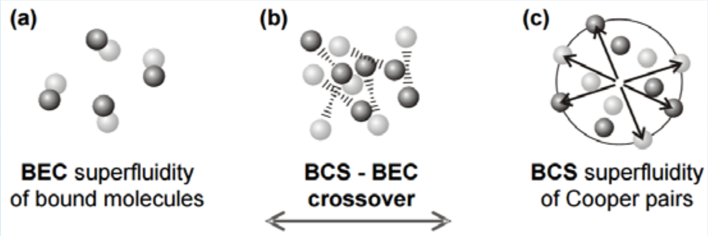
Michael Gehm

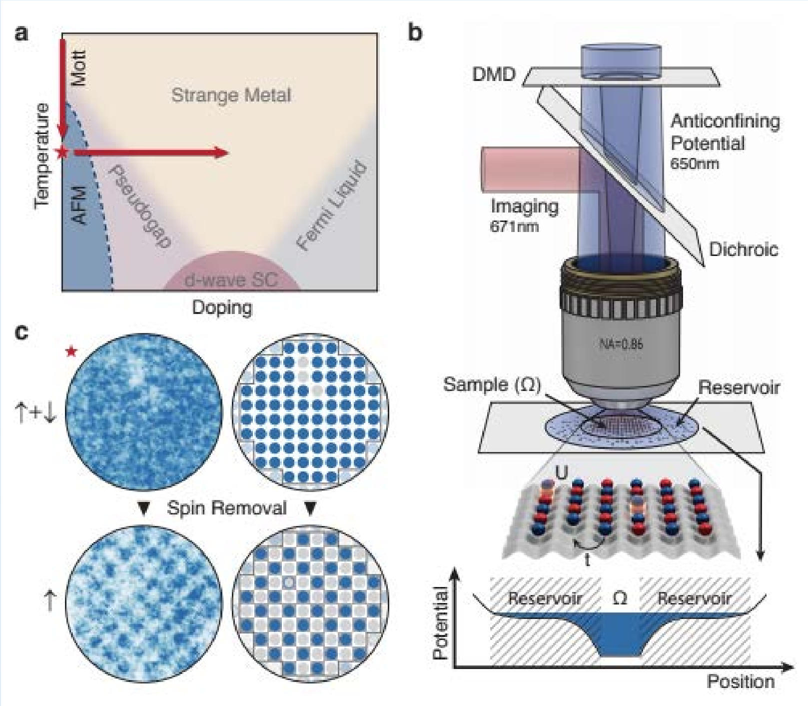
pseudo-spin states

Many experiments are based on spin-polarized gases
(all population in one hyperfine state)

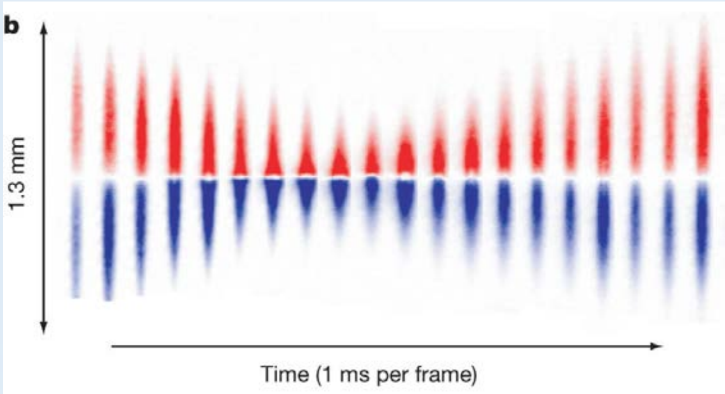
Lots of interesting physics based on spin mixtures

Jin group, BEC-BCS





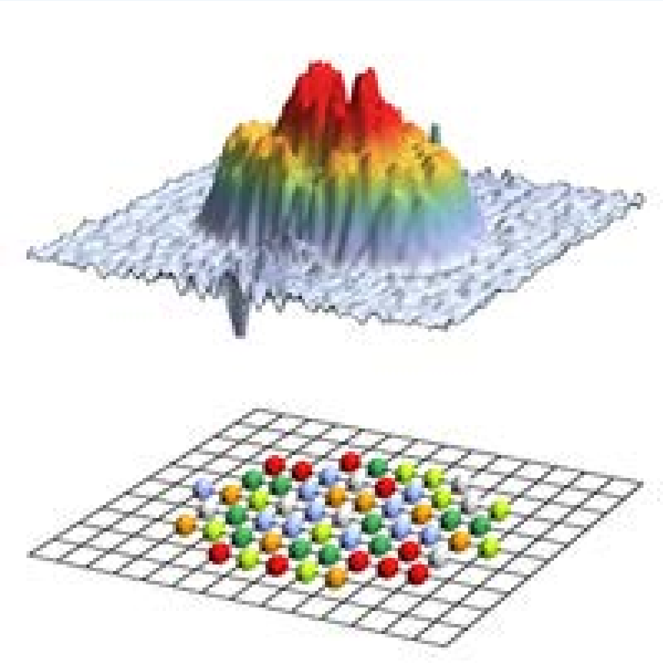
Greiner group, AFM ordering & …



Zwierlein group, Fermi mixture at unitarity

pseudo-spin states

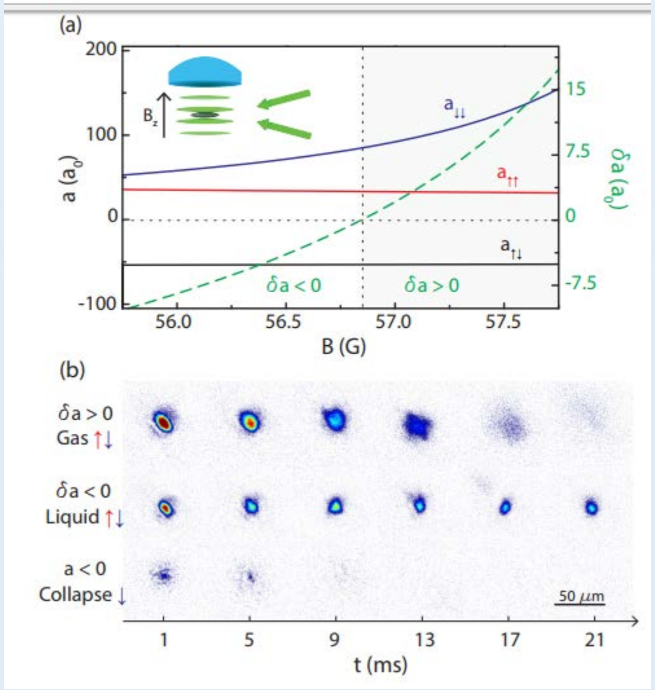
Unlike electrons, not limited to only two spin states



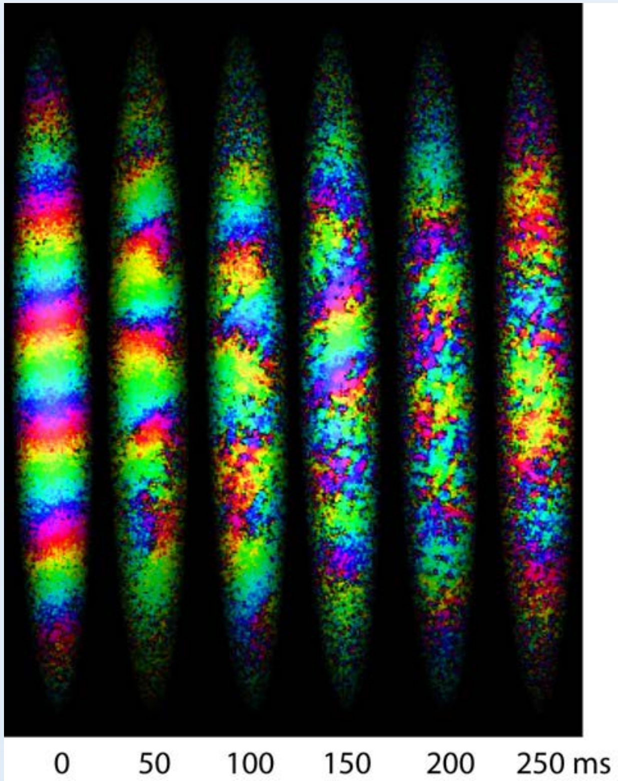
SU(N) Mott insulator (Folling, Fallani, Takahashi, etc.)

pseudo-spin states

Many bosonic mixture experiments too



Tarruel group, quantum droplets



Stamper-Kurn group, spontaneous spin textures

hydrogen hyperfine structure

Ground state:

$L = 0$

$S = 1/2$ for the lone electron

$I = 1/2$ for the lone proton

$\vec{F} = \vec{I} + \vec{S} \quad (l = 0)$

hydrogen hyperfine structure

Ground state:

$L = 0$

$S = 1/2$ for the lone electron

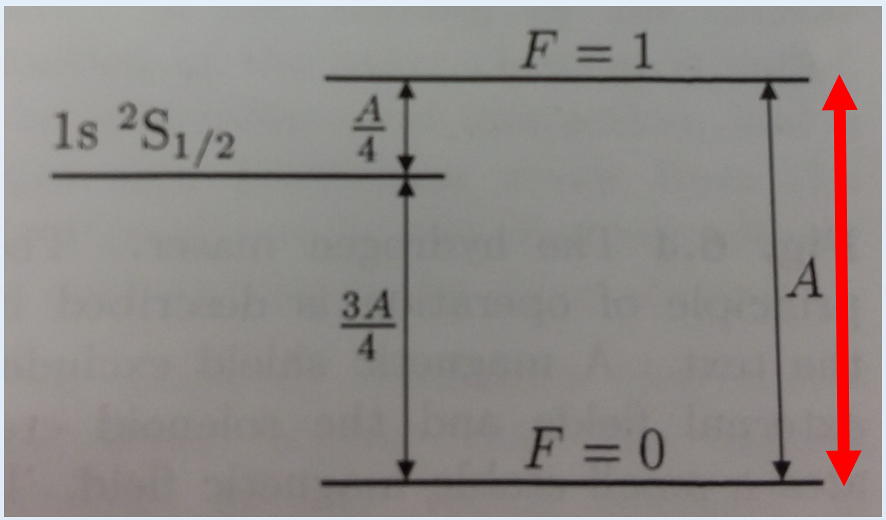
$I = 1/2$ for the lone proton

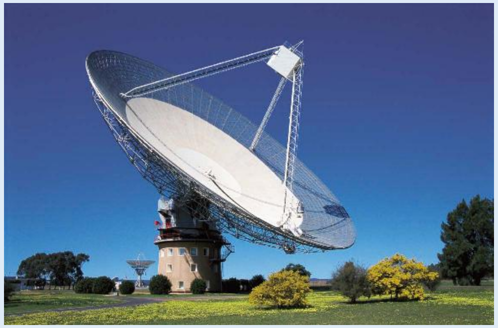
$\vec{F} = \vec{I} + \vec{S} \quad (l = 0)$

$F = 0$ or 1

$\Delta E / h \approx 1.42\,\mathrm{GHz}$

$\lambda \approx 21\,\mathrm{cm}$

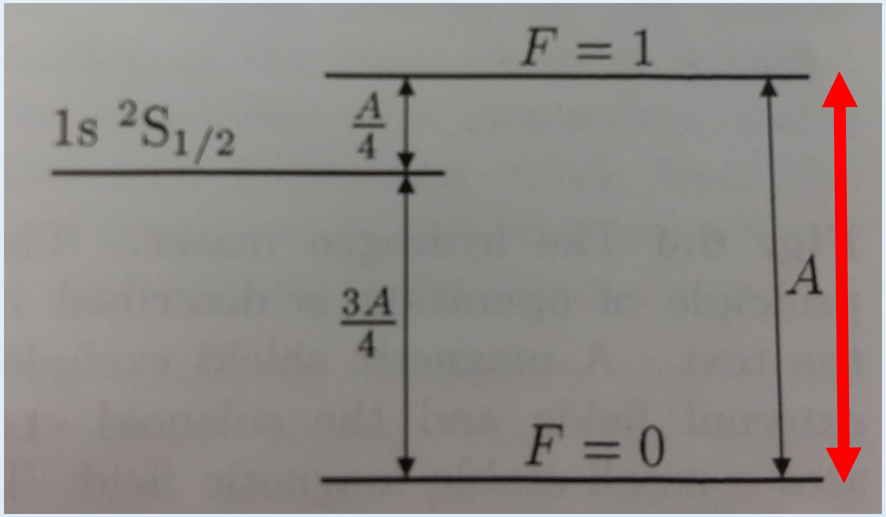




really important to observational astronomy

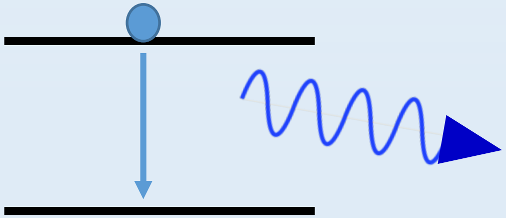
Importance in radio astronomy

F = 1 states are easily excited in thermal equilibrium at T_{space} ~ 3K



$$\Delta E / h \approx 1.42\,\text{GHz}$$

$$\Delta E / k_B \approx 68\,\text{mK}$$

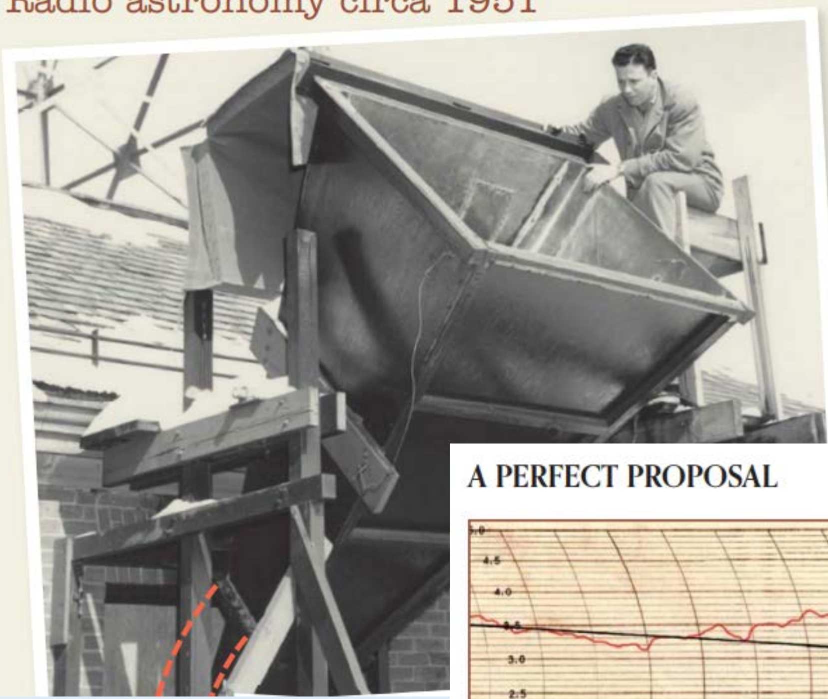


Excited states can undergo spontaneous emission → very small decay rate, but there's a lot of "stuff" out there (hydrogen makes up most of baryonic matter)

$$\Gamma / 2\pi \sim 10^{-15}\,\text{Hz}$$

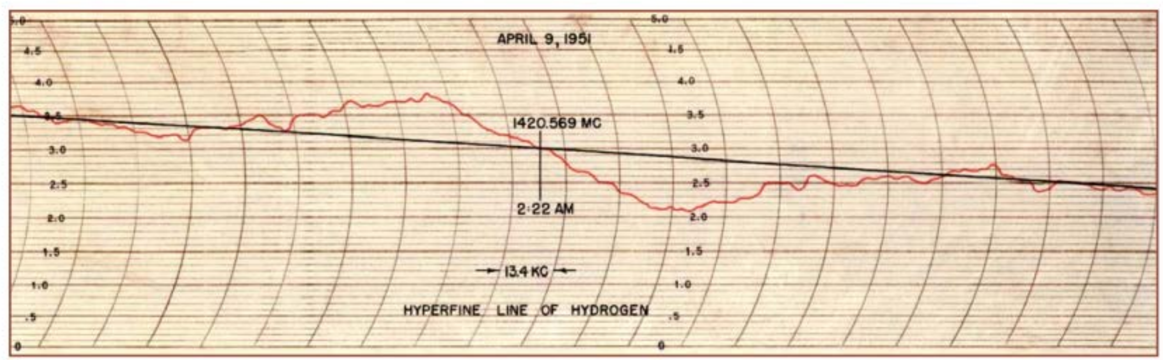
radio astronomy at 21 cm

Radio astronomy circa 1951



HAROLD "DOC" EWEN provides scale for the microwave horn antenna, which was made from copper-clad plywood and set on the fourth-floor parapet of Harvard University's Lyman Laboratory. Ewen added

A PERFECT PROPOSAL

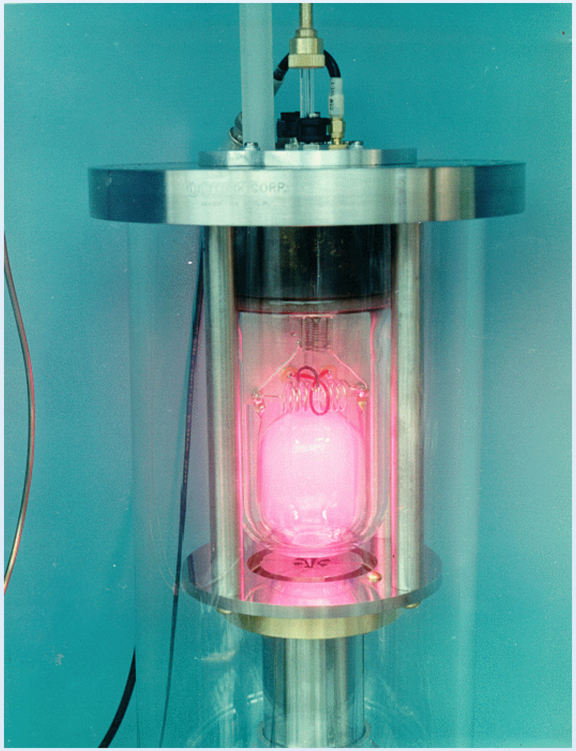


THE GALACTIC HYDROGEN EMISSION SIGNAL at 1420 MHz (21 cm), as traced in red on an electromechanical chart recorder less than three weeks after its discovery. The modulation technique causes the trace to have a positive and then a negative peak. The sloping black line approximates the receiver's drift over the 20-minute observation. (Reproduced from H. I. Ewen, "Radiation from galactic hydrogen at 1420 megacycles per second," PhD thesis, Harvard U., 1951, fig. 18.)

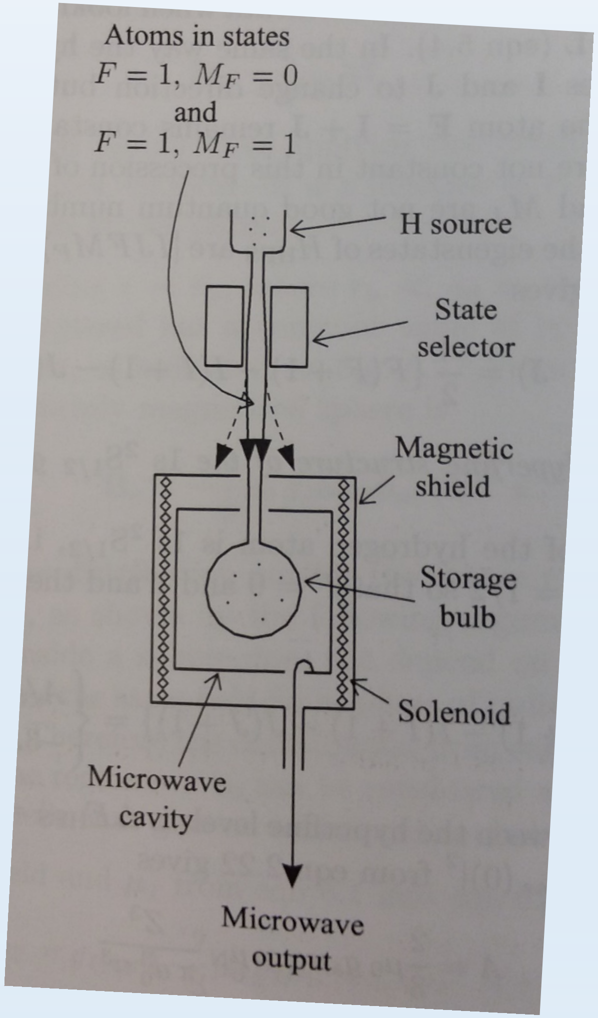
This was even before the hydrogen maser was invented!

the hydrogen maser

Not the best clock / freq. standard,
inaccuracy due to collisions with walls

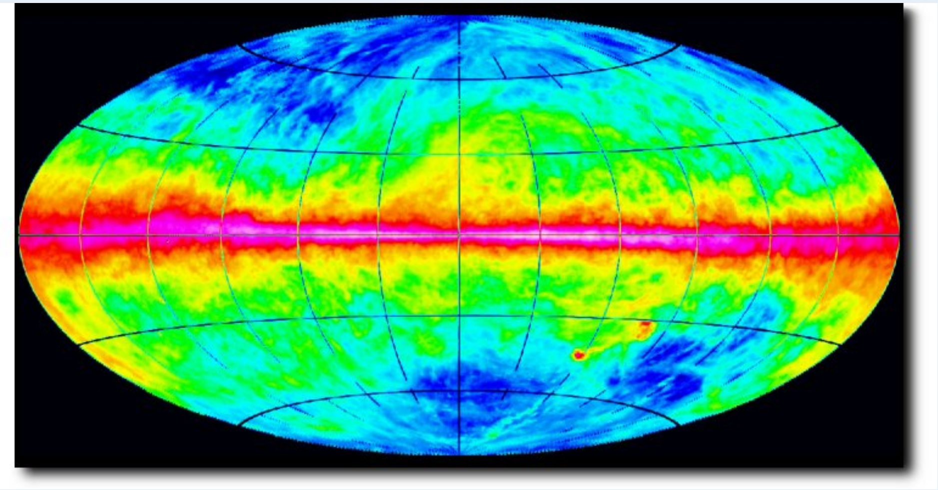


Microwave Amplification by Stimulated Emission of Radiation

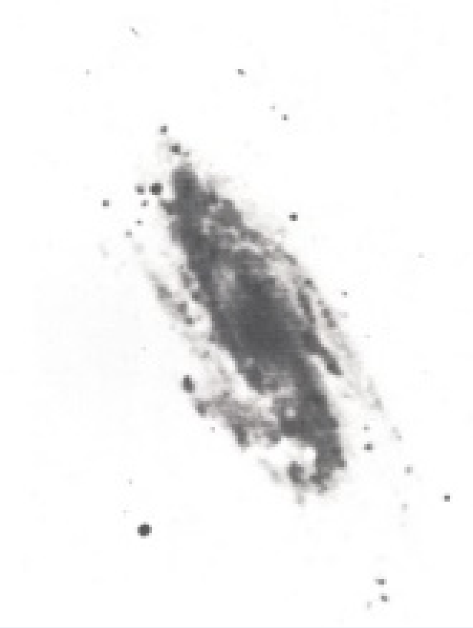


$\Delta E/h$ = 1,420,405,751.7667(9) Hz
(measured by comparison to Cs clock)

radio astronomy at 21 cm



Milky Way



NGC 3198

radio astronomy at 21 cm

Image at freq 1

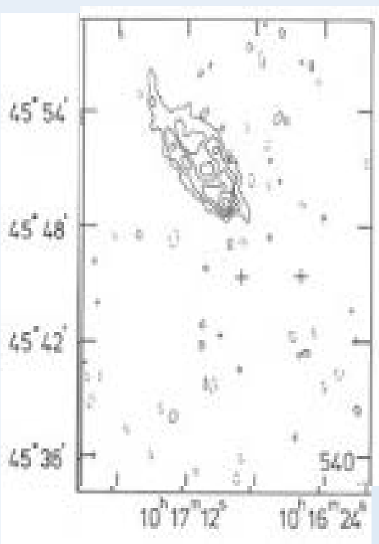


Image at freq 2

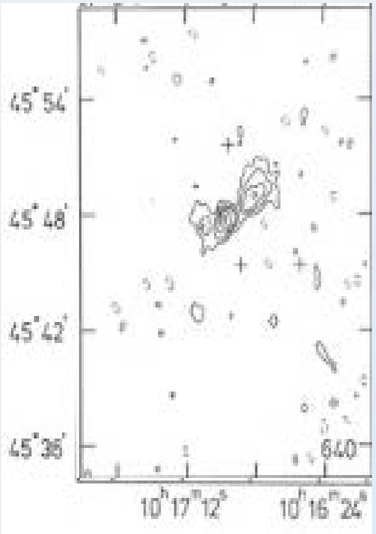
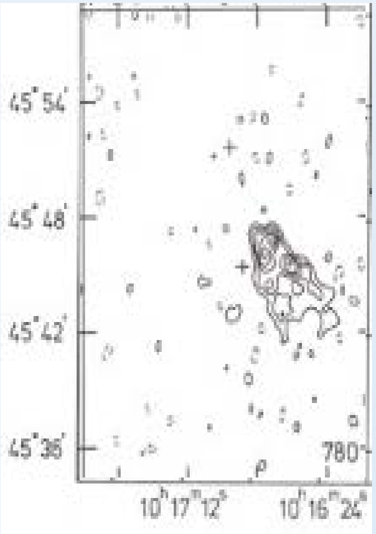
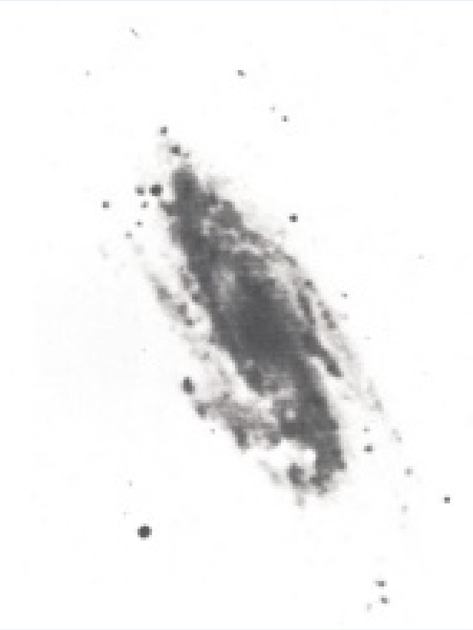


Image at freq 3



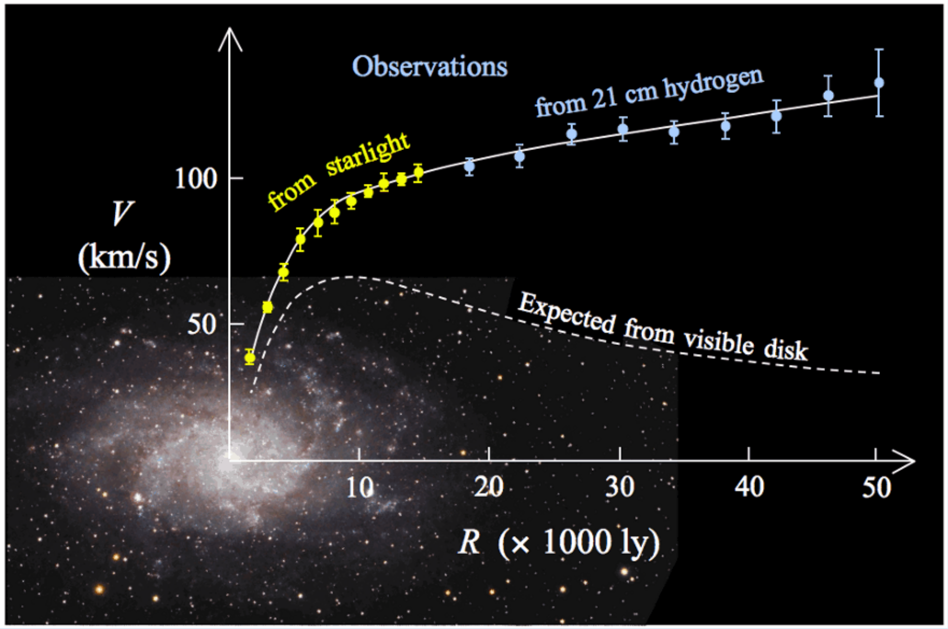


Detect galaxy rotation through Doppler shifts

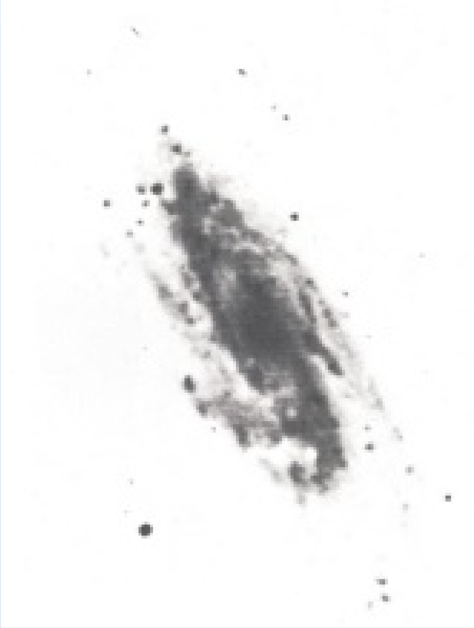
NGC 3198

https://ned.ipac.caltech.edu/level5/March05/Bosma/Bosma4_4.html

evidence for dark matter



Stefania.deluca of Wikimedia Commons



NGC 3198

https://ned.ipac.caltech.edu/level5/March05/Bosma/Bosma4_4.html

Hyperfine constants A_{hfs}, B_{hfs}

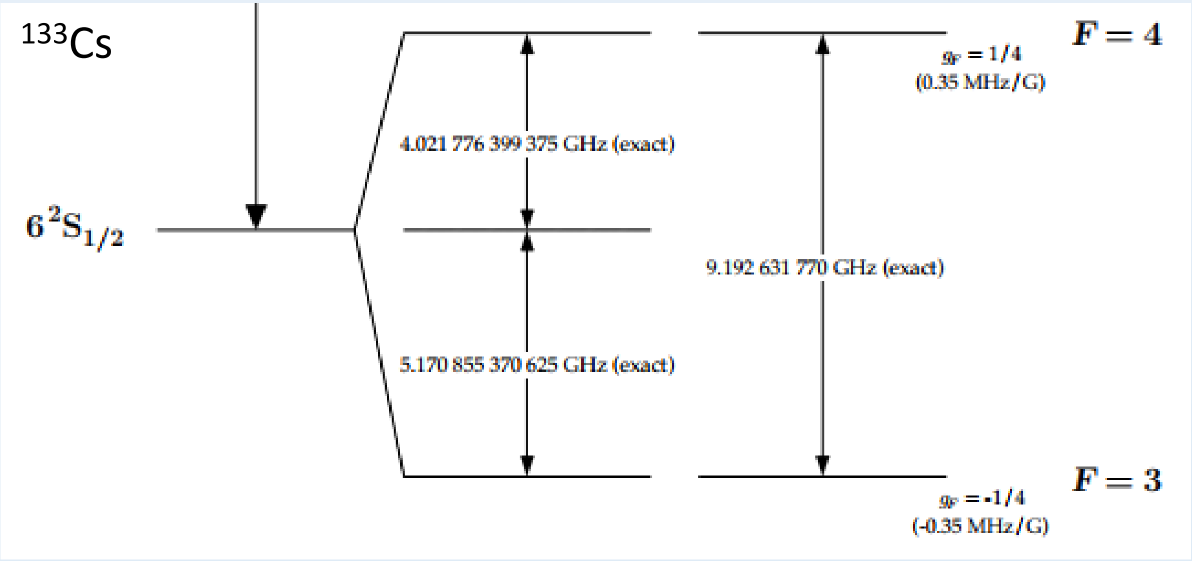
Note the range of nuclear spins values and the large variations in A_{hfs} values

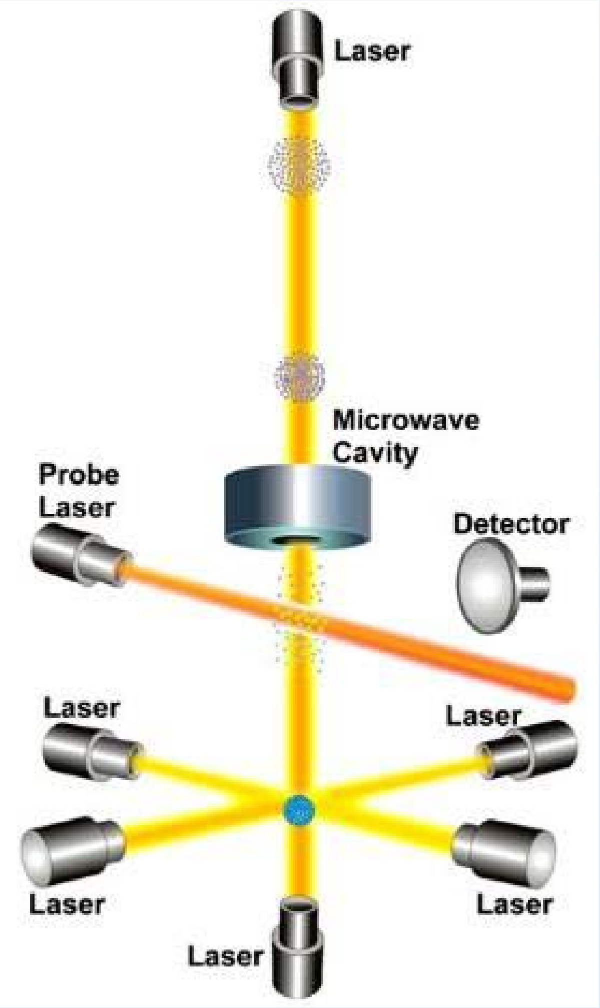
Element	Abundance	I	F_g ($J_g=1/2$)	A (MHz)	ΔE_{fs} (GHz)	F_e ($J_e=1/2$)	A (MHz)	F_e ($J_e=3/2$)	A (MHz)	B (MHz)
^{1}H	99.985	$1/2$	0,1	1420.405	10.968	0,1	59.18	1,2	23.67	–
^{6}Li	7.5	1	$1/2, 3/2$	152.137		$1/2, 3/2$	17.375	$1/2, 3/2, 5/2$	−1.155	−0.10
^{7}Li	92.5	$3/2$	1,2	401.752	10.091	1,2	45.914	0,1,2,3	−3.055	−0.221
^{23}Na	100	$3/2$	1,2	885.813	515.53	1,2	94.3	0,1,2,3	18.69	2.90
^{39}K	93.26	$3/2$	1,2	230.859	1730.4	1,2	28.85	0,1,2,3	6.06	2.83
^{40}K	0.0117	4	$7/2, 9/2$	−285.731		$7/2, 9/2$	–	$5/2, 7/2, 9/2, 11/2$	−7.59	−3.5
^{41}K	6.73	$3/2$	1,2	127.007		1,2	–	0,1,2,3	3.40	3.34
^{85}Rb	72.17	$5/2$	2,3	1011.910	7123.0	2,3	120.72	1,2,3,4	25.009	25.88
^{87}Rb	27.83	$3/2$	1,2	3417.341		1,2	406.2	0,1,2,3	84.845	12.52
^{133}Cs	100	$7/2$	3,4	2298.157	16611.8	3,4	291.90	2,3,4,5	50.34	−0.38

TABLE C.4. Fine- and hyperfine structure constants for the various alkali-metal atoms. The parameters A and B can be used in Eqs. 4.2 and 4.3 to calculate the shift and the splitting from the hyperfine interaction. The values for A and B are from Ref. 28.

Metcalf & van der Straten, Laser Cooling and Trapping

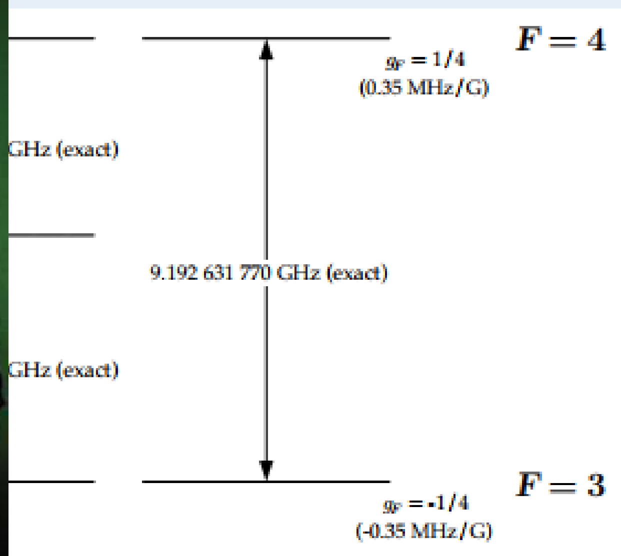
the cesium fountain clock

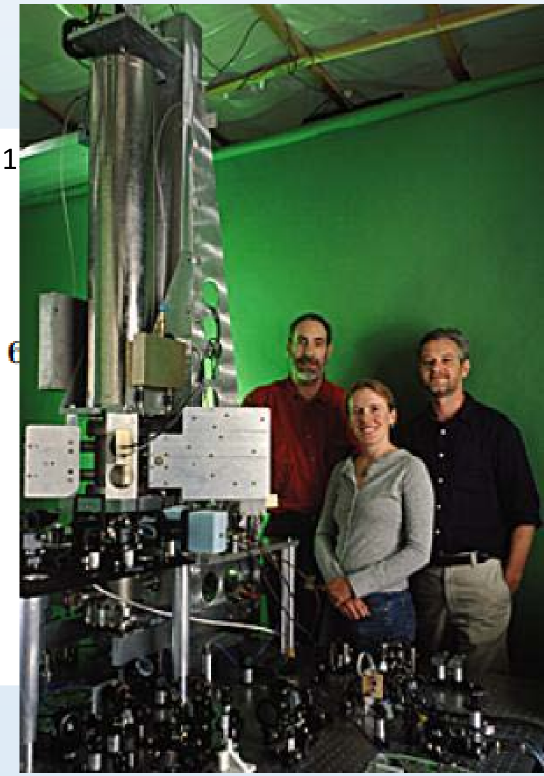




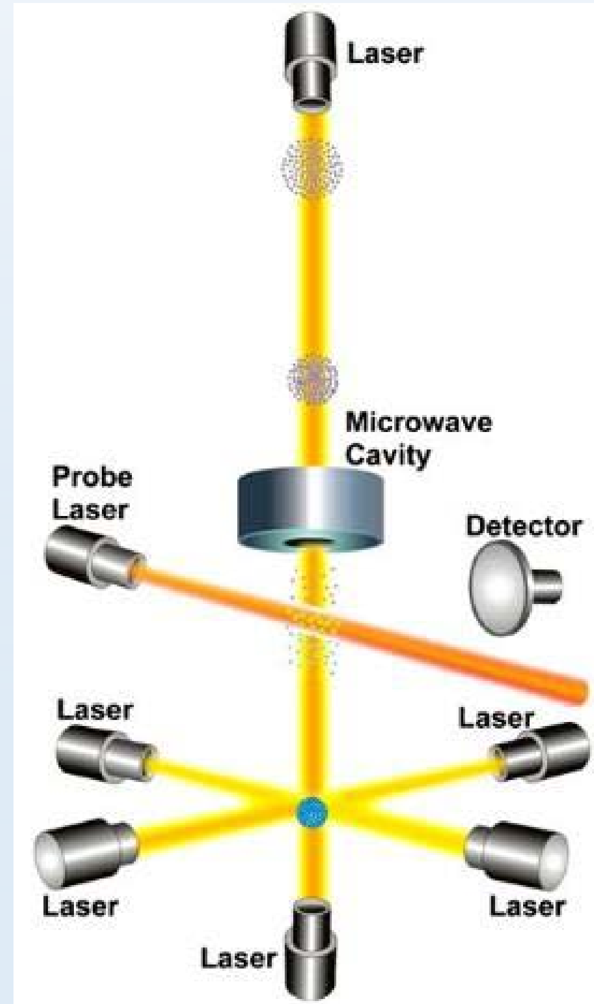
ΔE determines the SI second (and meter)

the cesium fountain clock





NIST F1



ΔE determines the SI second (and meter)